Fermi National Accelerator Laboratory

FERMILAB-FN-605

Neutron Dose in the SDC Hadron Calorimeter

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August 1993

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

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1. Introduction

The neutron background in SDC has been the subject of long standing interest [1]. Recently, rough estimates of the dose of neutrons in the SDC calorimeters have been made [2]. Clearly, the neutron background is serious, and may rival the dose in the EM compartment due to neutral pions.

This note refines the dose estimates in the SDC detector [3] based on recent studies undertaken by the SDC Neutron Task Force, which has mostly concerned itself with shielding for the muon system [4]. These refined estimates of the neutron fluence are compared to simple hand estimates, and the implied dose is calculated in an improved fashion.

2. EM Dose Estimate

The energy flow dE into a unit area dA, dE/dA, can be estimated assuming that the SDC calorimeters occupy a rapidity on the minbias "plateau" with a density D of pions per inelastic event, each of which has a transverse momentum of <Pt>. The total number of interactions in time T is $R_I T = 10^{17}$ for 100 years at SSC design luminosity. For a simplified SDC geometry of a cylindrical cavity of radius R and 1/2 length Zo, the energy flow is;

$$\begin{aligned} \frac{dE}{dA} &= \frac{(R_I T) D < Pt >}{2\pi L_0^2} \\ L_0^2 &= R^2 \quad , Barrel \\ &= Z_0^2 \tan^3\theta \quad , Endcap \end{aligned} \tag{1}$$

Note that dA is not the projected perpendicular area element, but the element of calorimeter area on the cylindrical surface.

For example, for D = 7 pions per unit of rapidity, with <Pt> = 0.70 GeV, and 10^{17} total interactions, the energy flow at $\eta = 3$ is ~ 4.4 x 10^{17} MeV/(cm^2). For reference, 1 Mrad is 6 x 10^{13} MeV/gm of deposited energy.

In order to find the dose in the SDC EM calorimeter compartment, one needs to find how the neutral pions deposit energy in the plastic scintillator. The neutral pion energy is assumed to be 1/3 of the total. The EM shower produces Nmip equivalent mips in the plastic at EM shower maximum [2], where Nmip is about = 10 mip/GeV. The mip deposit dE/dx of ionization energy per unit length. We assume that the length is the tile thickness τ (0.4 cm) divided by $\sin\theta$ in the barrel to get the total path length. Since the dose is the deposited energy/weight, the dose in the EM compartment due to neutral pions showering at EM shower maximum is;

$$\begin{aligned}(Dose)^{\pi^o}_{EM,SM} &= \frac{(R_I T) D < Pt >}{2\pi}\left(\frac{N_{mip}}{3}\right)\frac{dE}{d(\rho x)}\frac{1}{L_1{}^2} \\ L_1{}^2 &= L_0^2 \sin\theta\,,\ Barrel \\ &= L_0^2 \cos\theta\,,\ Endcap\end{aligned} \tag{2}$$

For example, the dose is ~ 0.2 Mrad at $\eta = 0$ and ~50 Mrad at $\eta = 3$ for 100 year operation at SSC design luminosity, using Nmip=10/GeV and $dE/d(\rho x)$ = 2 MeV/(gm/(cm^2)). The EM doses are the largest in the SDC calorimeters, but not by so large a margin as one might expect, as will be seen in what follows.

3. n Fluence Estimate

The neutron fluences are difficult to estimate from first principles. Several [4] estimates have been made using elaborate Monte Carlo codes. These codes yield roughly consistent results [4], but uncertainties of a factor at least 2 remain. The fluence, Fn, is normally quoted as the fractional kinetic energy, dT/T, in neutrons/(cm^2) for some number of minbias interactions;

$$\begin{aligned} TdFn / dT &= a \\ Fn &= a\, \ell n(T\max / T\min) \end{aligned} \tag{3}$$

If the fractional energy spectrum is constant, and = a, over the range in neutron kinetic energy = T from Tmin to Tmax, then the integral fluence Fn is easily obtained.

In the most simple minded estimate [2], the number of 1 MeV neutrons produced per GeV for incident hadrons is Nn (Nn ~ 6 n/GeV). Since 2/3 of the energy flow, dE/dA, is due to charged pions, the fluence of evaporation neutrons is;

$$Fn = \frac{2}{3} Nn \left(\frac{dE}{dA} \right) \tag{4}$$

The fluences given by the LAHET [4] code are shown in Fig. 1. In the barrel region the rates are quite constant, while in the endcap, the $1/\theta^3$ behavior expected from Eq. 1 and Eq. 4 is evident. The rates shown in Fig. 1 are for all T < 20 MeV. However, as seen in Fig. 2, there is a large component of thermal neutrons (T ~ eV) which are fairly benign for the scintillator in the calorimeter. For example, there is an integrated fluence of ~ 8 x 10^3 n/(cm^2·sec) in the energy range, Tmin = 0.3 MeV to Tmax = 3.0 MeV. Comparing Fig. 1a and Fig. 2, of the 4.5 x 10^4 n/(cm^2·sec) in the barrel region, only 1/5.6 of that total fluence is due to neutrons with T near 1 MeV.

The fluence for neutrons in the calorimeter cavity (tracking volume) is shown in Fig. 3. Note that the total fluence is comparable to that seen in Fig. 1, but the distribution in T (Fig. 2 vs Fig. 3) differs. For example, the "1 MeV" differential fluence of evaporation neutrons, TdFn/dT is 3000 n/(cm^2·sec) from Fig. 2 in the calorimeter, compared to 30000 n/(cm^2·sec) from Fig. 3 in the cavity where the tracking volume is located. This effect may be due to "crosstalk" of η from forward absorbers migrating into the tracking volume [4]. The barrel EM dose would then be expected to be larger than the HAD η dose.

In what follows the LAHET fluences will be used, as they are explicitly evaluated at hadronic shower maximum. However, there is clearly some uncertainty in the quoted numbers, and more work needs to be done before one may consider the SDC calorimeter neutron fluences to be firmly and reliably estimated.

The integrated fluences obtained from the LAHET work [4], and from Eq. 4 are shown in Fig. 4. The agreement is good in the barrel region, $|\eta| < 1.4$. Both estimates display the $1/\theta^3$ rise in fluence in the endcap. However, the LAHET numbers are up to 5x larger than the hand estimate. The origin of this discrepancy is not clear. The major assumption made in the hand estimate was that the neutrons were detected at the point of creation. The fact that both estimates tend to agree at $\eta = 1.4$ and $\eta = 3$ (boundaries) may indicate that this assumption is deeply flawed. Transverse neutron diffusion may be sufficient to explain the apparent discrepancy [4].

4. n Dose Estimate

The plastic in the SDC calorimeter is particularly susceptible to slow neutrons. The free protons recoil after np elastic scatters, and transfer that fraction of the hadron shower carried by the evaporation neutrons, rather efficiently, into the scintillator. The np elastic cross section [5], may be parameterized as;

$$\begin{aligned} \sigma_{np} &= \sigma_0 (T_0 / T)^{\alpha} \\ \sigma_0 &= 4b \\ T_0 &= 1MeV \\ \alpha &= 0.57 \end{aligned} \tag{5}$$

where, the cross section at 1 MeV is 4 barns. Note that, if the recoil proton has 1 MeV of kinetic energy, its range is ~ 20 μm in the plastic. Therefore, the transfer of recoil proton energy to the plastic is very efficient and local.

The probability to interact is given by the np elastic cross section, Eq. 5, and by the n fluence, Eq. 3. A factor, FACT, is adopted to convert the tile thickness traversed from normal incidence (τ = 0.4 cm thick scintillator tiles) to distance in the scintillator for uniform and isotropic illumination of the tiles by neutrons.

A small Monte Carlo progam was written to evaluate FACT. Tiles of area 10 cm x 10 cm (x,y) and 0.4 cm thick were illuminated isotropically and uniformly. The total path length in the plastic was recorded. The mean value was 1.04 cm, or a factor, FACT = 2.67. The Monte Carlo results are shown in Fig. 5. As seen in Fig. 5a, the minimum distance is 0.4 cm, corresponding to normal incidence, but substantially larger distances do occur. The distribution of path lengths is shown in Fig. 5b. In what follows, a value of FACT fixed to the mean value is used. Note that the only assumptions which go into the evaluation of FACT are the tile geometry (area vs thickness) and the isotropy of the neutron illumination.

Integrating the fluence (Eq. 3), convoluted with the np probability (Eq. 5) over the range of T from Tmax to Tmin, the dose due to neutrons at hadronic shower maximum is;

$$(Dose)^n_{HAD,SM} = a\left[\frac{T_{max}^{1-\alpha} - T_{min}^{1-\alpha}}{(1-\alpha)T_0^{-\alpha}}\right]\left(\frac{N_0\sigma_0}{A_{CH}}\right)\left(\frac{FACT}{2}\right) \tag{6}$$

In Eq. 6, No is Avagadros number and A_{CH} is the effective number of nucleons in the polystyrene scintillator. The other symbols appearing in Eq. 6 have been previously defined. The factor 1/2 refers to the mean fraction of the neutron energy given to the recoil proton in an elastic np collision.

Numerically, for Tmax = 0.3 MeV and Tmin = 3.0 MeV, with α and To as given in Eq. 5 and using Eq. 3, one finds that Eq. 6 simplifies to;

$$\begin{aligned}(Dose)^n_{HAD,SM} &= \left[\frac{T_{max}^{1-\alpha} - T_{min}^{1-\alpha}}{\ell n(T_{max}/T_{min})(1-\alpha)T_0^{-\alpha}}\right]Fn\left(\frac{N_0\sigma_0}{A_{CH}}\right)\left(\frac{FACT}{2}\right) \\ &\sim Fn\left(\frac{N_0\sigma_0}{A_{CH}}\right)\left(\frac{FACT}{2}\right)\end{aligned} \tag{7}$$

For example, in this case, a fluence of 10^{15} n/(cm$^2\cdot$100yr) causes the scintillator to bear a dose of ~ 4 Mrad due to np elastic scattering.

5. Soft Photon Effects

There are many soft photons in the hadronic calorimeter due to nuclear de-exitations. At an energy T of 1 MeV the dominant process by which these photons interact in the calorimeter is by Compton scattering, with a cross section in carbon of ~ 1 barn/atom [6]. The recoil electrons deposit energy in the tiles. However, a 1 MeV electron has a 20 cm mean free path in plastic [6], as compared to the 20 μm range of a 1 MeV proton. The fluence of photons is roughly 1/3 the fluence of neutrons [4] in both the SDC barrel and endcap.

Therefore, the expected dose due to photons is smaller than that due to neutrons. The flux (fluence) is lower and the cross section is lower. The mean free path in plastic is 20 cm for gammas, roughly 5 cm for neutrons. The dose ratio for photons to neutrons is roughly 15%.

$$\frac{(Dose)^{\gamma}_{HAD}}{(Dose)^{n}_{HAD}} \simeq \left(\frac{F\gamma}{Fn}\right)\left[\frac{t\lambda_{\gamma A}}{(N_0\sigma_0 t)/A_{CH}}\right](2) \tag{8}$$

It is assumed in Eq. 8 that the γ energy is entirely absorbed ("exchange" peak for the e, rangeout in the plastic), while the neutron deposits only 1/2 its energy through the recoil proton. Clearly, the ratio given in Eq. 8 is an overestimate, since the recoil electron will not typically stop in the scintillator. Given that the γ dose appears to be small, even when overestimated, it will be ignored in what follows.

6. EM/n Dose Ratio

The dose for the EM compartment can be evaluated using Eq. 2. The dose for the HAD compartment can be evaluated, for a given neutron fluence, from Eq. 7. Assuming that the neutron fluence can be related to the charged pion energy flux as in Eq. 4, one can obtain a second estimate of the neutron dose in the HAD compartment.

In this latter case, a simple (perhaps too simple) expression for the dose ratio in the EM/HAD compartment can be derived [2], and is given in Eq. 9.

$$\frac{(Dose)^{\pi^0}_{EM,SM}}{(Dose)^{n}_{HAD,SM}} \sim \frac{[dE/d(\rho x)]N_{mip}/ANG}{[T_0]\left(\frac{N_0\sigma_0}{A_{CH}}\right)(Nn)FACT}$$

$$ANG = \sin\theta\,,\ Barrel \qquad (9)$$
$$\cos\theta\,,\ Endcap$$

In Eq. 9, the symbols have all been defined previously, except for ANG. The angular factor, ANG, is needed to go from energy flow across an area to energy deposited with respect to normal incidence in the case of EM showers.

The numerical value of Eq. 9 is ~ 6 independent of η up to angular factors ANG, which are ~ 1 in the barrel and endcap. Therefore, in this model, the EM radiation dose always dominates [2]. The doses implied by the equations given above are shown in Fig. 6. The EM dose agrees with more sophisticated estimates [3]. The neutron dose follows the EM dose, reduced by a factor ~ 6 up to angular factors ~ 1.

Using the LAHET fluences as an independent estimate of the HAD dose, the two methods of dose estimation agree in the barrel, and at the inner and outer radial boundaries of the endcap within a factor ~ 2. There is a discrepancy within the endcap of a factor up to 5 between the two methods.

In any case, the maximum dose in the HAD compartment appears to be ~ 10 Mrad. There is also a dose due to ionization products in the hadron shower. This dose also has a maximum in the HAD endcap of ~ 10 Mrad [7]. The 2 sources of energy deposited in the plastic are assumed to be distinct, although some neutron - proton recoils (prompt) contribute to the calorimeter signal, and would thus, be double counted given the gate timing [7]. The separation of these 2 estimates is not attempted here.

7. Conclusions

The implications of the n fluence has been examined. Scintillator based calorimeters are particularly at risk, due to elastic proton recoils. The EM calorimeter has a total dose which is overwhelmingly dominated by ionization. For the hadronic calorimeter, the ionization dose is comparable to the n dose.

The 100 year ionization dose in the EM compartment is 0.2 Mrad at $\eta = 0$ and 50 Mrad at $\eta = 3$. The ratio of the doses at the 2 angles is ~ 250. The hadronic dose due to ionization is 0.05 Mrad at $\eta = 0$ and 10 Mrad at $\eta = 3$ [7]. The hadronic dose due to neutron elastic scatters is ~ 0.04 Mrad in the barrel, and ~ 10 Mrad at $\eta = 3$, although the precise dose depends on the details of the estimation of the fluence. Note that neutrons in the tracking volume will cause an additional dose in the barrel EM compartment.

It appears that the neutron dose roughly doubles the expected HAD dose in the SDC calorimeter up to a total of 20 Mrad at $\eta = 3$. Note that this value is only a factor of 2.5 below the dose absorbed by the EM compartment. Therefore, radiation damage is a serious issue for the SDC HAD compartment, as well as the electromagnetic compartments.

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Figure Captions

1. Neutron fluences from LAHET in neutrons/(cm^2·sec) x 10^{-5}. The points refer to all neutrons with kinetic energy T< 20 MeV.

   a. The SDC barrel region at hadronic shower maximum, radius = 240 cm. The fluence is shown as a function of axial position in the barrel, z in cm.

   b. The SDC endcap region at hadronic shower maximum, axial position z = 470 cm. The fluence is shown as a function of the radial position in the endcap, r in cm. The fluence in the endcap greatly exceeds that in the barrel.

2. The fluence of photons and neutrons, in particles/(cm^2·sec) x 10^{-5}, in the barrel region. The fractional energy spectrum, TdFn/dT is shown as a function of the kinetic energy power = p, where T is in MeV^p. For both the barrel and endcap, the photon/neutron ratio is ~ 1/3. The neutrons of interest for radiation damage are the evaporation neutrons with energies of about 1 MeV. Thermal neutrons are relevant to long term neutron activation.

3. The fluence of neutrons, in neutrons/(cm^2·min bias event), in the barrel region (tracking volume). The fractional energy spectrum, TdFn/dT is shown as a function of the kinetic energy, T in MeV. The data comes from Ref. 4. Both thermal and evaporation neutrons are evident, as in Fig. 2.

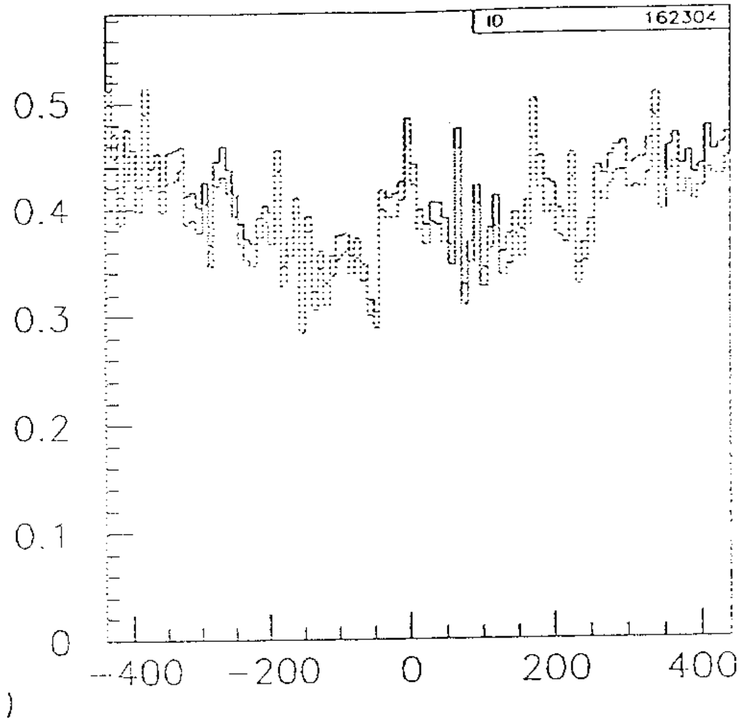
4. The fluence of neutrons in neutrons/(cm^2·100 yr) for the SDC calorimeters exposed to SSC design luminosity for 100 years. The fluence for LAHET (Fig. 1) and for the hand estimate (Eq. 4) are shown as a function of η. The agreement is good in the barrel region and at the endcap boundary, η = 3.

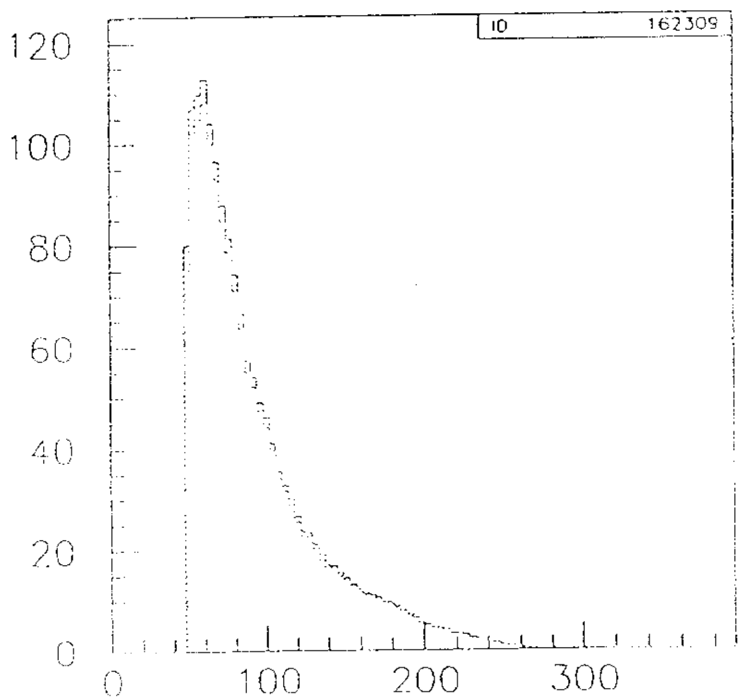
5. Estimates for the mean path length in a scintillator tile exposed to a uniform and isotropic illumination using Monte Carlo methods.

   a. Total path length in the tile as a function of impact point x, integrated over y. The tile is 10 cm x 10 cm (x,y) in area, and 0.4 cm thick. Edge effects are evident in the plot.

   b. The distribution of the total path length in the tile. The mean is 1.42 cm, for a tile thickness of 0.4 cm, leading to a factor, FACT = 2.67.

6. The dose in Mrad for 100 year operation of the SDC detector as a function of the pseudorapidity location of the calorimeter, η. The EM dose (o) is obtained from the estimate given in Eq. 2. The neutron dose estimate follows from Eq. 9 (*) or from Eq. 7 (+) using the LAHET fluences shown in Fig. 4. Clearly, the EM dose exceeds the HAD dose at all angles, but not by a large fraction.





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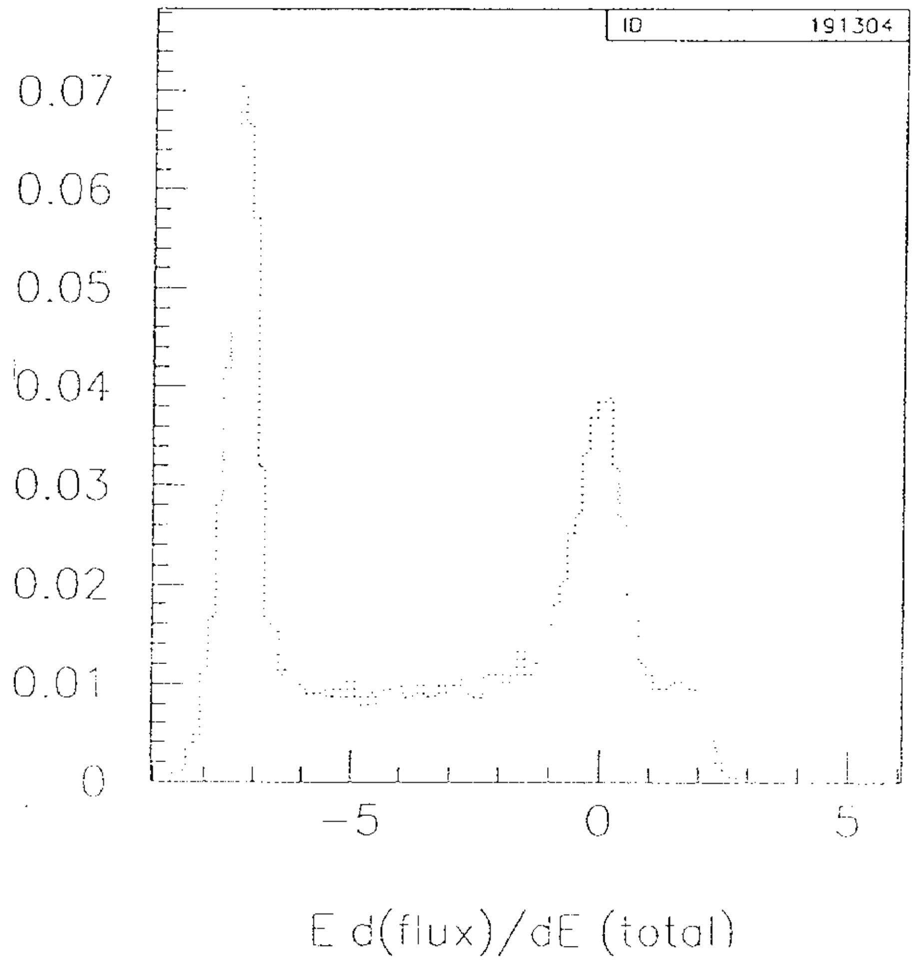

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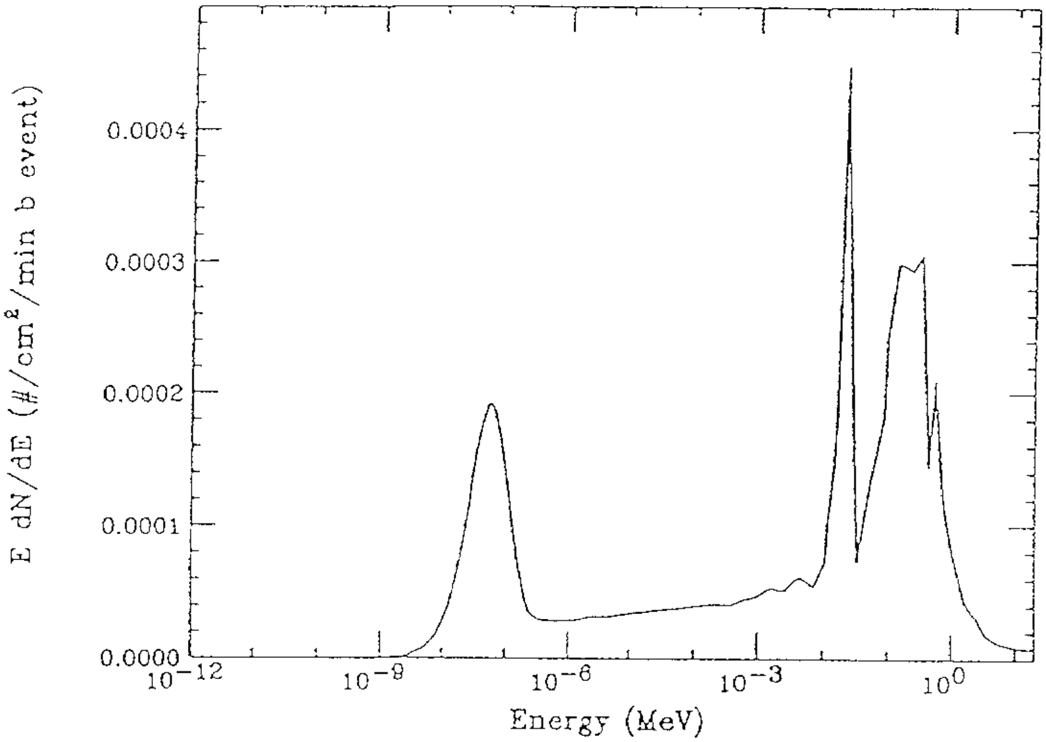

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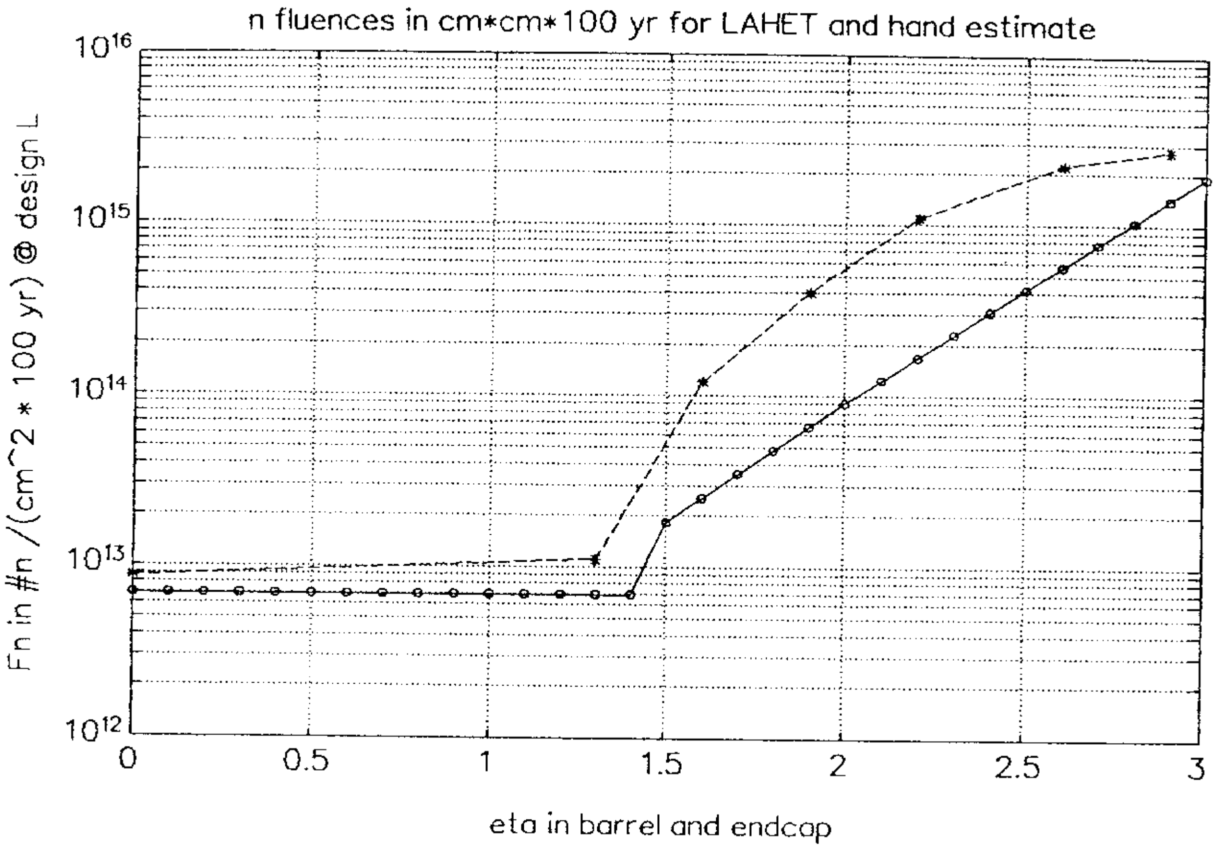

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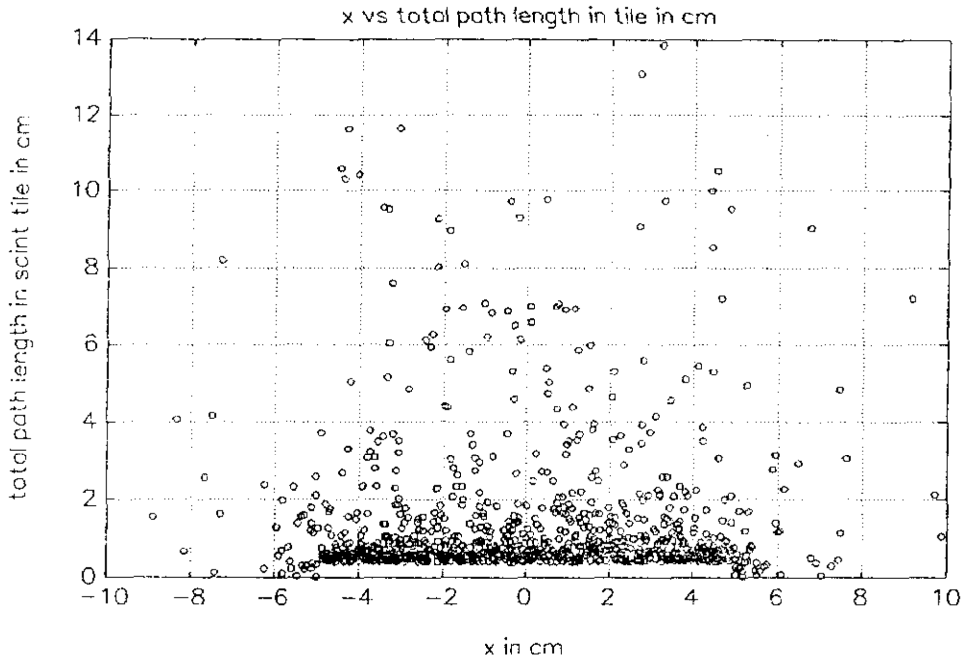

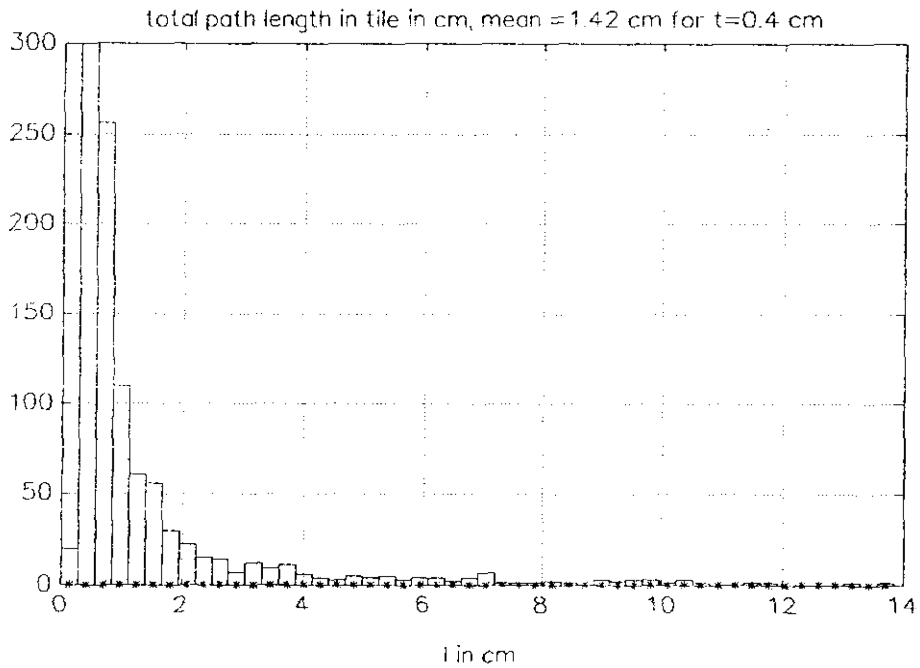

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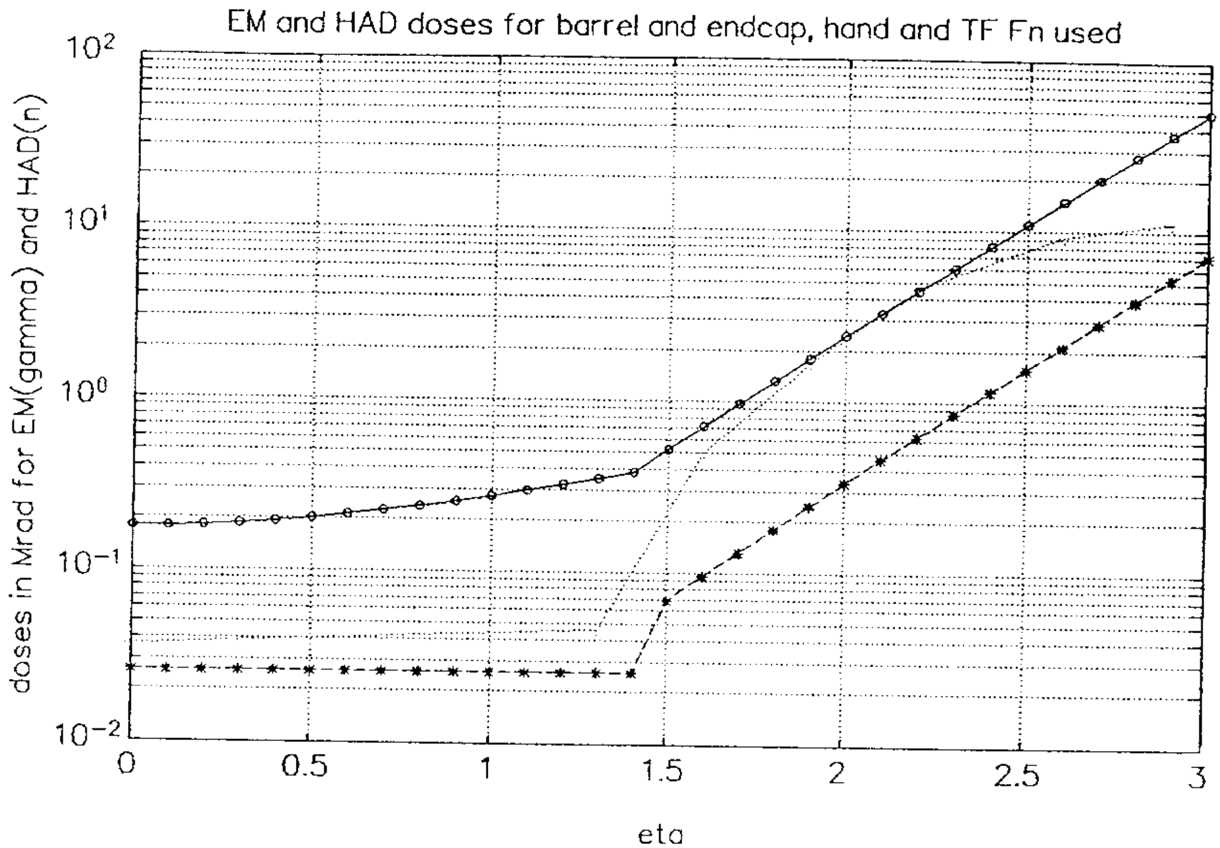

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